DOCUMENT RESUME

ED 468 195 SE 065 340

AUTHOR	Leonard, William J.; Gerace, William J.; Dufresne, Robert J.; Mestre, Jose P.
TITLE	Concept-Based Problem Solving: Combining Educational Research Results and Practical Experience To Create a Framework for Learning Physics and To Derive Effective Classroom Practices.
INSTITUTION	Massachusetts Univ., Amherst. Physics Education Research Group.
PUB DATE	1999-07-15
NOTE	28p.; Taken from the Teacher's Guide (Supplement B) to accompany "Minds-On Physics: Motion."
AVAILABLE FROM	For full text: http://umperg.physics.umass.edu/ gemsFolder/umperg2/CBPSP.pdf.
PUB TYPE	Guides - Non-Classroom (055)
EDRS PRICE	EDRS Price MF01/PC02 Plus Postage.
DESCRIPTORS	Concept Formation; *Constructivism (Learning); Elementary Secondary Education; *Experiential Learning; Instructional Effectiveness; *Physics; *Problem Based Learning; Problem Solving; Science Education; Teaching Methods; Thinking Skills

ABSTRACT

This paper identifies five types of learning experiences which are relevant to understanding students' grasp of concepts and principles. These include exploring existing concepts, honing and clustering concepts, developing analytical and reasoning skills, developing problem solving skills, and structuring knowledge in memory. Each of these learning experiences is presented with research results and some of the instructional methods and classroom techniques identified for a rich learning environment. Changes in teaching approaches require new roles for both teachers and students. This paper suggests a way for teachers to model for students and presents a student-centered process for learners to extract knowledge from experience. (Contains 49 references.) (YDS)

Concept-Based Problem Solving

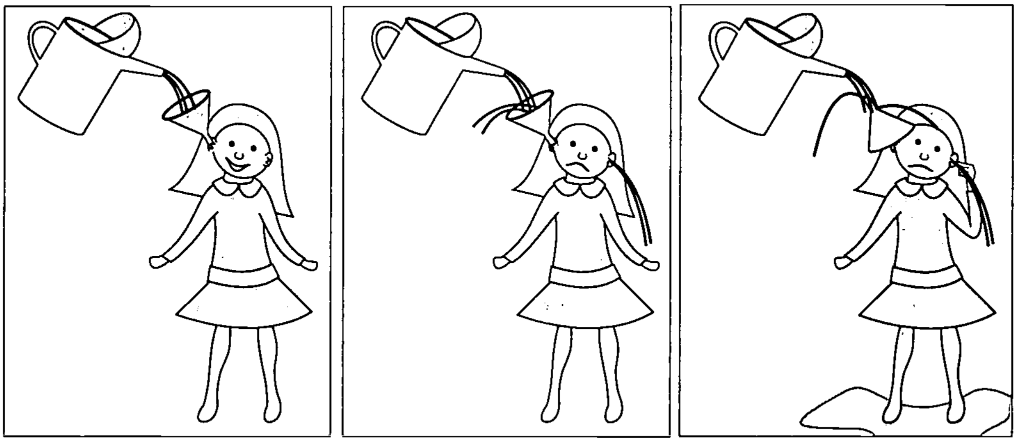
Combining educational research results and practical experience to create a framework for learning physics and to derive effective classroom practices

William J. Leonard, William J. Gerace, Robert J. Dufresne & Jose P. Mestre

Department of Physics & Astronomy, Box 34525
University of Massachusetts -- Amherst, MA 01003-4525 USA

July 15, 1999

Images can convey the truth about a situation powerfully and succinctly, so we offer you the following set of images. An old image of instructional practice is shown on the far left, although it is still prevalent today. It presumes that the teacher can simply pour knowledge into a student's head. This image is at least 300 years old and has not changed significantly during that time. The drawing in the middle shows a more likely representation of the current state of instructional practice [adapted from A. Van Heuvelen, 1992]. When someone tries to pour knowledge into a student's head, little is retained. Our view of common instructional practices is represented on the right. In particular, there are two features of the drawing worth noting. First, the finger in the ear means that the student is trying to retain the knowledge but, lacking the skills needed to do so, fails. Second, the inverted funnel means that common modes of instruction create a serious mismatch between the student and the teacher, which causes very little meaningful communication to occur.



Taken from Teacher's Guide to accompany Minds•On Physics: Motion

The irony of physics instruction is that although students solve lots of problems they do not generally develop problem-solving skills. Rather, solving lots of problems encourages and reinforces formulaic approaches and superficial learning. We believe that both deep understanding and proficient problem solving stem from being able to analyze situations conceptually. Our approach, called concept-based problem solving, shifts the focus of instruction from pure problem-solving tasks to tasks that target beneficial cognitive processes.

To us, the goal of instruction should be to take students through a sequence of learning experiences that takes account of students' pre-existing notions and gradually expands and hones those ideas until they are useful for analyzing situations and solving problems. A consequence of this approach is that students usually improve their reasoning skills and develop a deeper understanding of physics concepts and principles. We decompose this sequence of learning experiences into five stages each representing a level of cognitive development of the student. These instructional goals are listed below and will be explored in the first five sections of this supplement.

I. Exploring Existing Concepts

II. Honing and Clustering Concepts

III. Developing Analysis and Reasoning Skills

IV. Developing Problem-Solving Skills

V. Structuring Knowledge in Memory

A mixture of instructional tactics or modes is useful for targeting different stages. Good instructional modes encourage active engagement of the student and stimulate beneficial cognitive processes. The eleven modes that we find most useful are listed below.

- *Use Predict & Show (inadequacy of old model)*
- *Explain (draw, discuss, describe, summarize, etc.)*
- *Communicate about the learning process*
- *Use Multiple Representations*
- *Explore Extended Contexts*
- *Use Compare & Contrast*
- *Use Classify & Categorize*
- *Generate Multiple Solutions*
- *Plan, justify, and strategize*
- *Reflect (evaluate, integrate, extend, generalize, etc.)*
- *Make forward and backward references*

In this supplement there are 9 sections in all, each addressing a particular instructional goal. (The first 5 are listed above.) For each section, there are specific research results and pedagogy that are relevant for understanding it. Also included are recommended

instructional modes and classroom practices that are particularly useful for accomplishing the specific objective. The last four sections of this supplement are:

VI. Assessment: Formative vs. Summative

VII. Active Roles for Students

VIII. New Roles for the Teacher

IX. Meta-communicating with Students

I. Exploring Students' Existing Concepts

Research results. Students come into our classrooms with deeply held conceptions of how the world operates, many of which survive despite instruction, and often they co-exist side-by-side with "scientific" conceptions. These alternative conceptions generally arise because the human mind seeks patterns, and so students naturally form a conceptual framework to account for and cope with their experiences. Prior conceptions have been shown, in many instances, to impede learning of more formal frameworks. Prior conceptions can be difficult to uproot, often retained even after a concerted effort has been made (by instructors) to dislodge them [for reviews and bibliographies, see Mal92, McD84, Pfu91, Mes91, Mes94].

Pedagogy. Constructivism is a philosophy that states simply that all knowledge is constructed as a result of cognitive processes within the human mind. Radical constructivism takes this one step further by asserting that no amount of stimuli, experience, thinking, or communicating with others can prove that there exists an external reality. Science, of course, presumes its existence and seeks to describe and explain its nature and behavior.

The premises of constructivism are:

- Knowledge is constructed, not transmitted. Only information can be transmitted.
- Prior knowledge impacts learning. Existing frameworks determine what people notice, how they interpret what they notice, and how they construct new knowledge.
- Initial understanding is local, not global. New ideas are necessarily introduced and understood only in a limited context.
- Building useful knowledge structures requires effortful and purposeful activity. Meaningful learning requires active and thoughtful engagement.

For pedagogic purposes, the premises of constructivism may be rephrased as follows:

- Students have an established world view, formed by years of prior experience and learning.
- Even as it evolves, a student's world view filters all experiences and affects all interpretations of subsequent observations.

- Students are emotionally attached to their world views and will not give them up easily.
- Challenging, revising, and restructuring one's world view requires much effort.

The first step in the learning process, therefore, is to make teachers and students aware of their world-views. The more teachers know about students' individual conceptual frameworks, the better they can reveal the limitations of those frameworks, and the more likely they will be able to induce students to re-think and re-formulate their own world-views [And87, DiS88, Gla89, Gla92a, Res83, Res87, Rit97, Sch90].

Instructional Modes. Some useful modes for exploring students' existing concepts are:

- Use Predict & Show (inadequacy of old model). When students predict the outcome of a demonstration or experiment they are more committed to the activity and they are less likely to withhold judgment, i.e. waiting for the teacher to interpret it for them. By predicting an outcome, students often reveal the features of a situation they are focusing on and show what features they consider most relevant for understanding it. Although each student's world view often remains implicit during this instructional mode, an incorrect prediction can be ideal for demonstrating that their model has limited applicability.
- Explain (draw, describe, discuss). When students explain their reasoning for an answer, draw a picture of something, describe an observation, or discuss a demonstration, they are forced to use and make explicit whatever models they have for organizing their experiences. This instructional mode promotes self-awareness. Students cannot change their world views effectively unless they are aware of them.
- Communicate about the learning process. Students need to know that each of them has a unique perspective and that sometimes it is not self-consistent and can prevent them from learning efficiently and understanding deeply. They need to become active participants in the whole educational endeavor, from exploring existing concepts to structuring knowledge. Communication about learning is one way to help.

Classroom Practices. There are many ways that instructors can help students to reveal and confront their world views. These include:

- Have students use their own models to answer open-ended questions. Good questions reveal the limitations of their own models and motivate students to seek new conceptions. The answers inform the teacher and promote self-awareness among students.
- Tell students that they should not seek "right" answers; answers should be whatever each student believes is true. The hard part is creating a classroom atmosphere or environment in which students are comfortable taking risks and exhibiting their own thoughts, rather than feeling forced to give teachers what they (the teachers) want. In a constructive atmosphere, students are more likely to engage in the process of

learning and understanding. When questions involve common experiences, answers can often be tested, and science becomes integrated with students' everyday lives.

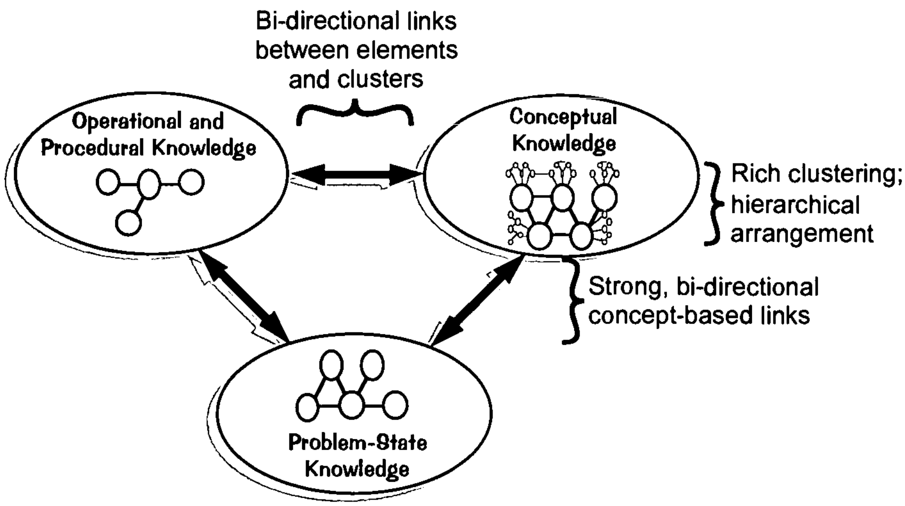
- Use small groups. Every student's world view does not need to be confronted by the instructor; another student can be as effective as the teacher—sometimes even more so—at uncovering inconsistencies in a world view. Small group discussions help students refine their explanations of the reasoning used to answer questions, and are usually less threatening than whole-class discussions. Using small groups makes students aware of diverse perspectives and promotes the idea that what everyone thinks is important. Perhaps most importantly, using small groups integrates language with science and experience. This can be critical for students whose mother tongue is different than the language of instruction, because many experiences are stored in the native language and discussions in the native language are more likely to access those experiences.

II. Honing and Clustering Concepts

Research results. The table below summarizes the main differences between the knowledge characteristics of experts and novices [Chi81b, Gla92b, Lar79].

Expert	Novice
Large store of domain-specific knowledge	Sparse knowledge set
Knowledge richly interconnected	Knowledge mostly disconnected and amorphous
Knowledge hierarchically structured	Knowledge stored chronologically
Integrated multiple representations	Poorly formed and unrelated representations
Good recall	Poor recall

Pedagogy. We have organized these results into a representation of the expert's knowledge store, as shown below.

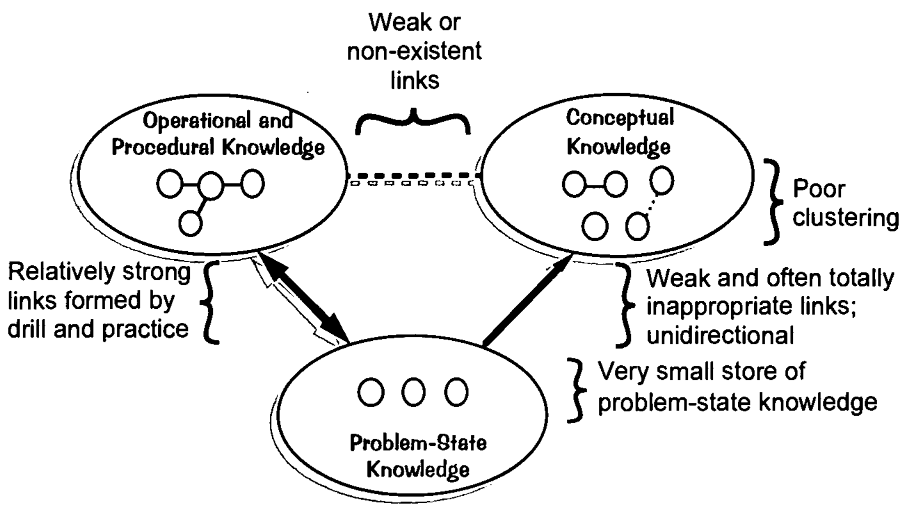


Domain knowledge has been divided into three general categories:

- Operational and Procedural Knowledge, such as the equation for kinetic energy, how to draw a free-body diagram, and how to find the normal force.
- Problem-State Knowledge, i.e., the features of a problem or situation used to characterize it. These can be surface characteristics, such as an inclined plane or a spring, or concepts and principles, such as energy is conserved.
- Conceptual Knowledge, such as force, mass, acceleration, kinetic energy, etc.

The expert has a rich, hierarchical (prioritized) clustering of conceptual knowledge. Concepts are linked to many different operations, procedures and problem situations, thereby refining and sharpening the meanings of the concepts. Experts use concepts to characterize problem situations and they also use concepts to judge the appropriateness and applicability of equations, operations, and procedures.

The novice has a very different knowledge structure, as shown below.



Unlike experts, novices generally have a poor clustering of concepts. Many links are inappropriate; others are non-existent. Some of the inappropriate links are extremely strong, which can lead to misconceptions. Many novices are familiar or have memorized a large number of equations, but they often remember them incorrectly or need to look them up in order to use them. They have been taught operations and procedures, but they are not yet proficient at using them and therefore often avoid using them. The links between equations and problem situations are relatively strong, but are based largely on the quantities (given and unknown) mentioned in the problem or situation.

In our view, one goal of instruction should be to help students develop a rich, concept-based structure of knowledge. To do this, students must learn how to hone (sharpen) and cluster (interrelate) ideas [Min92].

Instructional Modes. Here are some modes relevant for helping students hone and cluster concepts:

- Use Multiple Representations. A representation may be linguistic, abstract, verbal, symbolic, experiential, pictorial, physical, or graphical. A precise definition of any concept requires many representations, yet students often think that one representation (the algebraic) is sufficient. Students also tend not to interrelate representations, which often means their abstract physics ideas are not well connected to real-world experiences. Using different representations for the same knowledge, and having students translate between representations, helps students to interrelate ideas and to relate ideas to personal experience. For instance, write an equation on the blackboard and have students read it back to you (i.e., translate from the algebraic to the verbal representation). We especially like to use graphs because they are abstract, like equations, but can be understood qualitatively, like diagrams or pictures.
- Explore Extended Contexts. Initial understanding is necessarily limited by the context in which it is first introduced. The human mind naturally seeks patterns and tends to

generalize using those features that are most noticed. Students tend to focus on surface features and often generalize incorrectly as a result. Students also cannot easily re-evaluate their generalizations. Investigating a broad set of problem situations helps students to refine and abstract concepts; it avoids inappropriate or oversimplified generalizations. Students are more likely to use relevant features and to ignore irrelevant features after they have explored a range of contexts.

- Use Compare & Contrast. Like Extended Contexts, the goal of Compare & Contrast is the interrelation of knowledge. The difference is that while Comparing & Contrasting students are required to look explicitly for distinctions and commonalties between situations.
- Explain (describe, discuss, define). When students explain (and describe, etc.) their reasoning, they reveal the features they are using to organize their ideas. Explaining also helps students create connections between ideas, making their knowledge store more like an expert's.

Classroom Practices. The goal of these activities is to help students to refine and abstract their definitions of concepts, and to relate new ideas to ideas already learned. The following classroom practices should make this more likely:

- Use as many different representations as possible for the same concept. Using different representations helps students sharpen their understanding and provides alternatives for thinking about a concept. This can be especially important when a particular concept is needed to understand a new concept.
- Make sure the first two examples of something are the same only in the feature (or features) that is relevant for understanding it. Students are likely to notice many similarities between two situations. We cannot guarantee that they will notice what is relevant and ignore what is not. (And telling them what to notice and what to ignore is not sufficient!) For instance, many students believe that the normal force always points vertically upward, because all the examples they have seen have shared this feature. By taking greater care in choosing the first two examples of something, teachers can help students avoid oversimplified generalizations and confusion.
- Ask questions that probe the boundaries of students' knowledge. Learning occurs at the periphery of understanding when students attempt to use and relate partially formed ideas and work outwards from a core of well understood ideas. Learning cannot occur in the darkness and confusion of poorly formed ideas. For example, have students compare similar situations: is [something] the same or different? why? Change something about a situation; what else changes? Have students provide examples (preferably from their everyday experiences) in which the concept is or is not manifest.

III. Developing Analysis and Reasoning Skills

Research Results. Most beginning physics students do not appreciate the value of a conceptual analysis to solve problems. Instead, novices usually perform means–ends analysis. They focus on equations and start manipulating them in an attempt to isolate the desired unknown, often inserting numerical values from the very beginning of the process. Novices are distracted by the goal of determining the value of the desired quantity. In this mode, students often suffer from cognitive overload. They are so focused on answers that they have no mental resources left to think about problem solving [Duf92, Lar81, Lar83].

Pedagogy. The manner by which students learn is itself learned. What students know determines how they engage in problem-solving activities, and how they engage in problem-solving activities determines what they learn. Their approach to problem solving has been reinforced by years of rote learning, memorization, and regurgitation. Continuing to assign lots of problems does little to break this cycle. In fact, doing traditional problems can reinforce superficial attitudes and discourage students from desiring to understand [Bro89a, Tou95].

One solution is to structure problem-solving activities to shift the focus of students' attention away from getting an answer, and to communicate with students about learning so that they are looking for alternative patterns and explanations. For example, students must be made aware of their learning habits. Before students can use concepts to solve problems, they must learn how to use concepts to analyze situations and reason about them [Duf97].

Instructional Modes. Some modes useful for developing analysis and reasoning skills are:

- Use Multiple Representations. The essence of effective reasoning is finding the representation in which the result is obvious. For example, in many situations free-body diagrams are useful for comparing the magnitudes of forces. When students consider different representations and use them to analyze situations, their critical thinking skills are enhanced, which eventually leads to improved problem-solving proficiency.

- Use Compare & Contrast. It usually takes less time to compare two quantities or two situations than to compute a single quantity. Often, we can describe a situation without specifying enough information to determine unknown quantities, yet there is still enough information to make a comparison. (For example, consider a disk and a sphere having the same mass and radius rolling at the same speed along a horizontal surface. Upon encountering an incline, which would reach a higher maximum height?)

- Explain (summarize, discuss, listen, debate, argue). Good critical thinking skills can be developed and honed by having students explain their reasoning and by having them debate issues. Listening requires analysis and processing. Presenting counter-arguments to someone's line of reasoning further knits the structure of knowledge.

Reasoning necessarily involves concepts, so concepts become the vocabulary of explanations, eventually making qualitative analysis a viable tool for problem solving.

Classroom Practices. The following suggestions can help students focus their attention on concepts as being useful for understanding physical situations.

- Use goal-free activities. To reduce cognitive load and encourage reflection and deep thinking, students need to work on questions that do not require a numerical result. This makes it more likely that they will use concepts. Ask questions that can only be answered using concepts, or at least, can be answered most easily using concepts. Equations might be used, but usually they are not manipulated in order to solve for an unknown. For example, a definition might be used to determine how one quantity is related to another.
- Direct students' attention to the features of a situation most relevant for understanding it. For example, in one situation, energy might be the most relevant for understanding it, while in a similar one, momentum might be more relevant. Students might be focused on the surface similarities, and might not realize that different concepts are used. Analyzing situations encourages using scientific concepts and principles to organize knowledge.
- Use familiar or simple situations, or use the same situation to ask many different types of questions. Students invest a lot of mental resources in processing and storing the context in which a question is posed. When the situation is unfamiliar or complicated, there may be few resources left for students to analyze it. By using familiar or relatively simple situations, cognitive load is reduced. By re-using situations in many different problems and questions, students learn that the same situation can be analyzed and understood using many different concepts and principles, and they learn that surface features are not always useful for organizing knowledge.

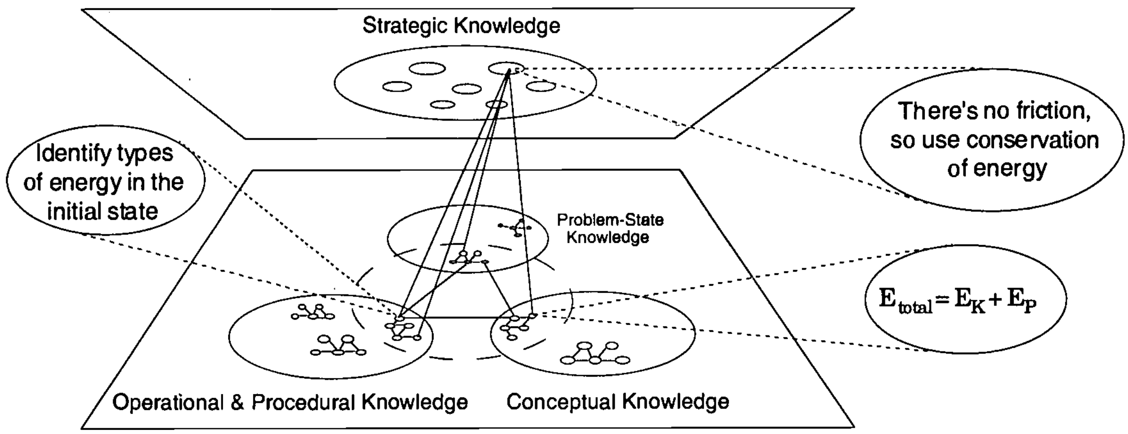
IV. Developing Problem-Solving Skills

Research Results. The problem-solving behaviors of experts and novices are very different, as summarized in the table below [Chi81a, Gla92b, Har89, Lar80a, Lar80b].

Expert	Novice
Conceptual knowledge impacts problem solving	Problem solving largely independent of concepts
Often performs qualitative analysis, especially when stuck	Usually manipulates equations
Uses forward-looking concept-based strategies	Uses backward-looking means–ends techniques

Has a variety of methods for getting unstuck	Cannot usually get unstuck without outside help
Is able to think about problem solving while problem solving	Problem solving uses all available mental resources
Is able to check answer using an alternative method	Often has only one way of solving a problem

Pedagogy. Below is a representation of strategic knowledge. Strategic knowledge links knowledge of problem situations, equations, operations, and procedures into a strategic element that guides the entire problem-solving process. Based on a conceptual analysis, decisions are made concerning what ideas should be focused on and which should be ignored. Students will not build strategic knowledge elements on their own. They must engage in structured problem-solving activities and they must reflect on the problem-solving process [Duf92].



Proficient problem solving is mostly about making choices — what to focus on, what principle to apply, what representation to use, what to ignore — yet most students have (at best) one way of solving any particular problem. Choices necessarily involve concepts, because it is concepts that are used to make comparisons. The more we can encourage students to perform qualitative analyses before solving problems, the more they will improve their problem-solving proficiency.

Instructional Modes. The following modes can be used to help students develop forward-looking problem-solving approaches and abandon backward-looking means–ends approaches:

- Use Classify & Categorize. This is similar to Compare & Contrast, except that the focus here is on sorting ideas or problems, and on labeling the resulting categories. Students must practice creating and recognizing classification systems. When students sort

items, choose names for their categories, and explain their systems, we increase the likelihood that they will use concepts to organize their knowledge.

- Generate Multiple Solutions. When students solve the same problem using different approaches, they learn to prioritize the approaches. For example, the algebraic representation is not always the most useful one for solving a problem, but students are generally not convinced of this.
- Plan, justify, and strategize. Very few relationships in physics are always valid. Many are derived or defined for a particular set of circumstances. (For example, the definition of kinetic energy as $\frac{1}{2}mv^2$ is true only for a point object or when the object is both rigid and not rotating.) Most students are not aware of the assumptions, conditions and circumstances that make a particular equation, operation, or procedure applicable. By having students plan their approach (without actually solving the problem), justify their approach, or develop a strategy, they learn the value of concepts and conceptual analysis for problem solving.

Classroom Practices. Here are some ideas to help teachers implement structured problem-solving activities.

- Choose problems that <u>require</u> a conceptual analysis to solve. Traditional problems are usually solved by applying one or more previously derived equations or by repeating standard procedures by rote. Understanding is not required. When problems <u>cannot</u> be solved using a formulaic approach, students learn very quickly that the most efficient method is by using concepts. This does not mean that the problems need to be difficult (though students will find them difficult at first). In fact, the best problems use simple or familiar situations and are relatively easy to solve with a concept-based approach.
- Have students explain <u>how</u> they would solve a problem. In the time it takes most students to solve a single problem, students can explain <u>how</u> they would solve a number of problems. This activity shows students (and the teacher!) what the students are focused on while problem solving, which impacts later discussions and allows the teacher to plan suitable interventions.
- Have students solve the <u>same</u> problem using different approaches. For example, many problems can be solved using either Newton's laws or Momentum Conservation. Solving the same problem using two different principles helps students learn new material and promotes comparison of methods.

V. Structuring Knowledge in Memory

Research Results. In a series of PERG studies, students solved problems by answering a series of questions arranged hierarchically. For instance, they were first asked, "Which of the

following would you use to solve this problem? Kinematics/Newton's Laws, Work–Energy/Conservation of Energy, Impulse–Momentum/Conservation of Momentum, or Angular Impulse–Angular Momentum/ Conservation of Angular Momentum." Depending on their answer to the first question, they would answer increasingly focused questions about the problem. Control groups solved the same problems and spent the same amount of time solving them as the test group. Two relevant results emerged from this study: Students constrained to solve problems hierarchically (1) were more likely to get the problems correct; and (2) were more likely to sort problems according to which principle was used to solve them [Duf92, Mes93].

Pedagogy. Traditional problem-solving tasks do not help students develop useful problem-solving skills. We believe the reason for this is that traditional problems do not stimulate beneficial cognitive processes. The core of our cognitive framework is this:

- Particular types of knowledge and knowledge structures are needed for proficient problem solving and deep understanding.
- Particular types of cognitive processes are required for the acquisition of conceptual knowledge and the building of useful knowledge structures.
- Activities should be designed to encourage desirable cognitive processes.

The ultimate goal remains proficiency at solving problems, but equally important goals are developing deep understanding of physical situations and the ability to analyze new or unfamiliar situations using physical principles. To accomplish these goals, the main focus of most activities is shifted away from problem solving toward cognition. We cannot guarantee that beneficial cognitive processes will occur, but we can make them more likely to occur. This, we believe, should be the focus of instruction [Duf97, Leo96a].

Instructional Modes. These modes can help students structure their knowledge for deep understanding and for efficient and effective problem solving.

- Make forward and backward references. Concepts require a long time and much experience to become fully formed. You cannot wait for students to completely learn one topic or idea before moving on to the next. By making forward references to material to be covered, you prepare the student for new material. By making backward references, you associate new material with established or partially established material, making knowledge interwoven and interconnected, rather than linear or chronological. By making forward and backward references, students can construct many pathways to the same ideas, thereby making knowledge more easily accessible for tests, quizzes, projects, discussions, and problem solving.
- Use Classify & Categorize. When students classify and categorize ideas, we can increase the sophistication of the ideas used to think about physics and physical situations. In particular, students are more likely to use physical principles and laws to sort problems and problem situations. The question is, "Are your students aware of

the categories that you believe are useful for organizing physics ideas?" If so, then they should be able to notice when two problems are solved using the same principle, even if the two problems look very different. If not, then using Classify & Categorize can reveal how students are sorting problems, and can lead to useful discussions about other possible organizational systems.

- Reflect (evaluate, integrate, extend, generalize, etc.). After most activities, students benefit from reflecting on what they've just done. What patterns have students perceived in the questions, situations, or problems presented? How will students approach similar situations in the future? What difficulties were encountered? What caused the difficulties? How will they overcome them in the future? How would they apply the ideas to... (a specified situation)? Can they connect the ideas to "real-world" events and situations? What general principles may be extracted from the learning experience? What have the students learned?

  Learning experiences often give students the necessary pieces of the "how-to-do-physics" puzzle, but many students will not attempt to fit the pieces together unless you ask them specifically to do it. Reflection helps students structure their knowledge as they are learning it.

- Communicate about the learning process. To learn physics (and many other subjects!) students must become self-invested in the learning process; they must become more self-aware and more self-motivated; they must know why learning physics is useful and important. These issues are handled by communicating about learning. Do students know how they learn best? Have they ever thought about what their greatest weaknesses (or greatest strengths) are? Do they know what the purpose of a particular activity is? Do they understand why concepts are so important? Do they know what is meant by "structured" knowledge? Do they know why structuring knowledge is useful? Communicating about learning helps motivate students and helps keep them engaged in the learning process.

Classroom Practices. These will help teachers help students structure their knowledge.

- Give students many opportunities for reflection. Reflection is an activity that teachers and other professionals usually perform on their own, often while engaged in another activity. Most students cannot reflect on problem solving (or any other activity) while doing it and they will not reflect on their own; they must be given time specifically put aside for reflection, and they must be given questions specifically designed to help them do it. There are many contexts students can reflect upon: the ideas raised in an activity or discussion they've just completed, problem solving, their learning styles, and the entire learning process, just to name a few.

- Give students the time needed to think about and discuss the interrelation and prioritization of ideas. Structured knowledge is richly interconnected and organized hierarchically, with the most important ideas serving as umbrella concepts for less important ideas. Structured knowledge leads to efficient and effective problem solving,

because concepts can be used to determine the applicability and appropriateness of equations, operations, and procedures. Structured knowledge also leads to deeper understanding.

- Give problems in which the surface features may be misleading. When the surface features of a problem suggest one approach, which is different from the most efficient or effective approach, students quickly learn that concepts are useful for organizing ideas. The problems do not need to be difficult, however, and the best ones involve situations that are easy to describe and easy for students to understand. The goal is to design problems that require a conceptual analysis to solve.

VI. Assessment: Formative vs. Summative

Research Results. In 1992, David Hestenes, Malcolm Wells and Greg Swackhamer awakened the physics education community with extensive data on student performance on their Force Concept Inventory (FCI) and Mechanics Baseline Test (MBT). They asked students at senior secondary level to answer questions about physical situations at the end of their physics instruction. The questions were relatively simple, and most teachers believed their students would get most — if not all — of them correct. Here's a typical question from the FCI:

> Two metal balls are the same size, but one weighs twice as much as the other. The balls are dropped from the top of a two-story building at the same instant of time. The time it takes for the balls to reach the ground below will be:
>
> (A) about half as long for the heavier ball;
> (B) about half as long for the lighter ball;
> (C) about the same time for both balls;
> (D) considerably less for the heavier ball, but not necessarily half as long;
> (E) considerably less for the lighter ball, but not necessarily half as long.

About half the students surveyed answered (A) for this question, and similar results were found for all the questions. The findings confirmed earlier findings about students' preconceptions and how difficult they are to dislodge through traditional instructional approaches. The overall results also strongly suggest two additional findings: (1) that teachers are generally not aware of the knowledge state of their students, and (2) that traditional assessment practices do not measure conceptual understanding [Chi81b, Har92, Hes92a, Hes92b, Kul91, Res92].

Pedagogy. The way we assess our students has far reaching consequences. If we wait until all material has been covered and use assessment only to test their proficiency, then students often come to feel evaluated, and therefore often fear examinations. They may learn little or nothing from the experience. They might discover what they know and what they don't know, but there's often little that they can do about it. The class has moved on to another topic, and there's no time put into the curriculum for students to catch up. If struggling students don't move on to the next topic with the rest of the class, they just get farther and farther behind.

Traditional or summative assessment has many virtues, but it should not be the only form of assessment used in the classroom. Formative assessment is different. Formative assessment is asking questions, not to evaluate, but to determine the current knowledge state of the learners, so that both teacher and learners may make adjustments if necessary to the structure and focus of future learning experiences [Kul91, NSF92].

Formative assessment serves many helpful roles. It can reduce the fear of students to being examined. It can encourage students to seek answers that make sense to them, rather than seeking answers that are "right". It can often be used to detect difficulties students are having before the difficulties inhibit learning new material. It informs the student and teacher of any limitations or confusion in the communication process. It can keep students more engaged in the learning process.

Instructional Modes. These four instructional modes are excellent for creating questions that inform the student and teacher, rather than evaluate.

- Explore Extended Contexts. When the context of a question is new and unfamiliar, we can more easily determine if ideas and concepts have been understood and abstracted. The context does not need to be complicated, just different.
- Use Compare & Contrast. Comparisons are often simple for teachers to develop and easy for students to answer. Many students will answer a comparison question without resorting to equations, and therefore, students often reveal their conceptual understanding with their answers. Limiting cases can often be used to challenge a student's world view and to encourage the student to rethink it.
- Use Multiple Representations. Using alternative representations further probes the boundaries of students' knowledge. A sketch or a graph is often more informative than a verbal explanation. Instead of asking students to compute the acceleration in a particular situation, have them describe five common situations in which an object is accelerating and five more in which an object is not.
- Explain. Having students explain their reasoning for an answer is often the best way to assess understanding and to determine what they are focused on. This can be done with any of the other instructional modes, and usually enhances the information gathered by any particular question.

Classroom Practices. Here are some ways to change assessment practices from summative to formative.

- Assess often. Frequent assessment informs teachers and helps them plan and structure interventions. It also promotes self-awareness and increases the motivation and engagement of students. Frequent assessment does not need to be highly structured, formal, or written. It can be informal and oral, taking place during individual or group work, and consisting of simple questions requiring short answers.

- "Assess" rather than "evaluate". To encourage thoughtful engagement among students, we must try to disentangle, at least somewhat, assessment from evaluation. Getting a question wrong should not necessarily result in negative consequences. Formative assessment consists of questions that attempt to measure a student's current state of knowledge and understanding, and therefore, cannot be "right" or "wrong" in the traditional sense. An answer that informs — i.e. an honest one — is preferable over an answer that meets the teacher's expectation. Only if a student is not being totally honest in his answer can his answer be considered "wrong".
- Use exams as a learning experience. Many teachers do not use tests and exams as an additional learning experience for students. Many also don't realize how much they can learn about students attitudes, abilities, and understanding during an examination. When used on exams, formative assessment measures how well students have generalized and how well they can apply their knowledge to new situations. Formative assessment on exams can also help teachers discourage students from rote-memorization and equation-manipulation.

VII. New Roles for the Teacher

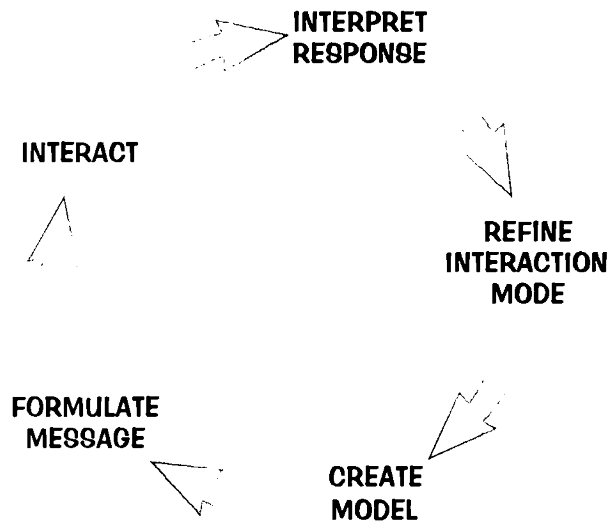
Research Results. Traditional approaches to teaching science consist of presenting material through lectures while students sit quietly "learning" it. This approach assumes that students can absorb scientific knowledge while passively listening to instructors. Teachers often model for students activities that are crucial in the practice of science, such as description, explanation, and prediction. Yet, students largely observe the teacher modeling these activities, rather than actively performing the activities for themselves. Many excellent science teachers present well integrated and structured knowledge to students, but students are not actively engaged in constructing such knowledge for themselves. Classroom observations at all levels indicate that teachers seldom take into account the conceptual knowledge previously constructed by students. Further, students' ideas, predictions, and explanations of science phenomena are not probed to determine whether the concepts being taught are in conflict with students' prior notions [Hew95, Mes94, Res83].

Pedagogy. Changes in instructional approach and assessment practices require new roles and responsibilities for teachers. We believe that instruction is more effective when the teacher and the learner are engaged in two-way interaction. This means that the school year should be more like a long conversation between students and teachers than a long movie that students are watching [Bro89a, Col89, Duf96].

When instruction is reformulated as a dialogue, teachers and students must all help maintain lines of communication, and must work to develop a common language and vocabulary for communicating. They must find ways to check that the message sent is the same as the message received (e.g., through formative assessment practices). Most

importantly, the teacher must learn how to model students so that he/she can interpret responses better and guide communication more efficiently. In other words, teachers should go into the classroom to learn rather than to teach. For instance, they can learn about their students, about common thought patterns, how to tease out misconceptions, and how to structure activities to maximize student engagement.

One way for teachers to model students is to follow the five-step cycle shown at right. At the beginning of the cycle, the teacher interacts with his/her students and interprets their responses. Based on the interpretation, the teacher makes any necessary changes to the learning environment and modifies his/her model of the students. Based on the model, he/she formulates a new question or learning experience and interacts some more with the students, where the cycle continues. Although the format has become bi-directional communication, the goal remains helping the student to structure his/her knowledge store.



Instructional Modes. The following modes can help teachers to make instruction closer to a dialogue and to model their students.

- Communicate about the learning process. Encourage students to participate in their own learning by helping to monitor communication. When confusion arises during a discussion with a classmate or teacher, have students consider alternate interpretations or definitions of terms. Discuss the importance of precision in communication and encourage students to look out for ambiguity.
- Reflect. Ask students to reflect on the learning process and on how effective communication is between you and them. When having trouble understanding a student, ask another to interpret the first. Similarly, when giving instructions, it is always helpful to ask a student to paraphrase what is being asked.
- Use Multiple Representations. Alternative representations enrich the communication process and using different ones helps students link and cluster ideas. Students should become proficient in using as many representations as possible, such as graphs, sketches, and equations. When words fail, ask students to draw a picture or graph or motion diagram.
- Explore Extended Contexts. Sometimes the best way to model students is to ask questions in unfamiliar contexts. This is usually because it is nearly impossible for the

student to know the answer already, but must first process the question, interpret the unfamiliar situation, analyze its features, and formulate an answer.

Classroom Practices. When the focus of instruction is shifted from teaching students to learning about them, many changes are needed in classroom practice. They include:

- Ask questions rather than deliver lectures. Lectures tell teachers very little about what students understand and what they don't. It's also hard to keep students' minds engaged and focused on learning while they are sitting passively listening to a lecture. (Few students can listen actively.) Asking questions has many advantages. First, a question must be processed, which often means that the student's mind is active. Second, the answer helps teachers model their students. Third, asking questions focuses attention on the student's structure of knowledge rather than the teacher's structure. Fourth, asking questions promotes student involvement and self-awareness.

- Foster active and reflective learning. What many teachers like about teaching is that their minds are active and reflective while doing it. And the students we often admire the most are the ones with whom we can interact, and for whom active engagement and reflection are common. Yet our daily classroom practices often discourage interaction, engagement, and reflection in students.

- Re-think traditional assessment procedures. The behavior we value in students must be encouraged and rewarded if it is to develop. New assessment practices are one way of reinforcing changes in instructional practices. Tell students what is correct about their response rather than what is incorrect.

- Become learning counselors. The best teachers guide students and structure learning experiences in order to maximize students' motivation, engagement, self-awareness, and thoughtfulness. Instead of trying to regiment students' ways of thinking and solving problems, good teachers are fascinated by the variety of students' outlooks and the myriad ways they have for making sense of their experiences.

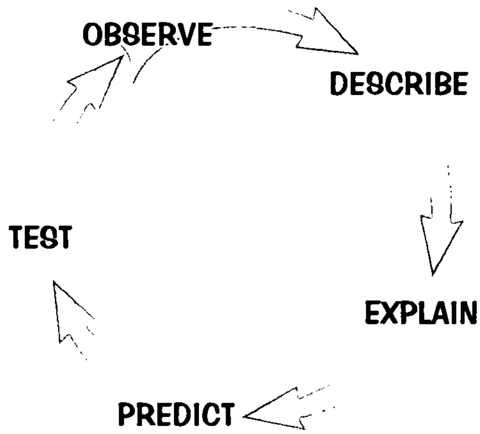
VIII. Active Roles for Students

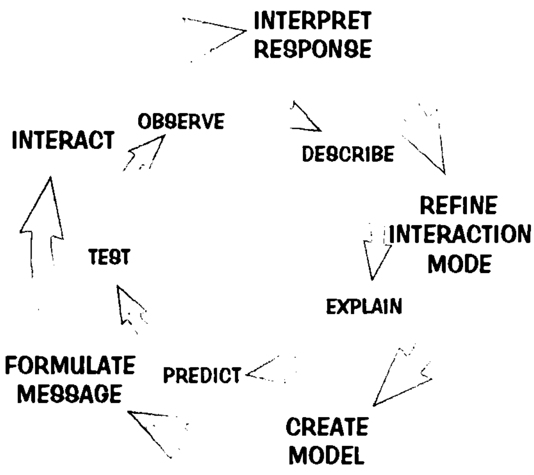
Research Results. Students come into our classrooms with established world views, reinforced by years of experience. These alternative conceptions, even though they are in conflict with the scientific concepts being taught, can be difficult to uncover and dislodge. Traditional instruction often results in a student's knowledge store that is amorphous, poorly interrelated, and equation driven [Chi81b, Lar79, Min92, Mes91, Mes94].

Research also indicates that each person's organizational scheme is unique, and that people often have difficulty using or fully appreciating another person's structure. The best students often seek patterns on their own, but most students need to have patterns pointed out to them explicitly [Bas89, Gic80, Gic83, Gic87].

Pedagogy. Knowledge is constructed, not transmitted. For instruction to be effective, students must actively process and reflect on their experiences, so that they can form useful knowledge structures. Instruction must take account of students' prior learning. Learners should be self-conscious and self-aware, and they should be fully engaged in the learning process. They can deliberately seek supplemental learning experiences, and they can be very effective at modifying their own world-views [Bro89b, Cam94, Cle93, Mes97, Wen97].

We recommend a reformulation of the educational endeavor into one that is process-oriented and learner-centered. The five steps at right represent a process students can use to extract knowledge from experience. In the first step, students observe something (or perhaps recall a prior experience). They then seek to describe it, thus exhibiting the features they are using to classify it. Students then explain their observation, preferably with some form of causal relationship. Based on their explanation, they predict what might happen in a related situation, and finally, they test it. When they observe the test, the cycle begins again.





This view of instruction is learner-centered. It takes into account the students' prior learning and modes of thinking and learning. The teacher is focused on helping students structure their knowledge. The teacher monitors the students and models them while they are engaged in learning experiences. The diagram on the left summarizes our view of the teacher and learner.

Instructional Modes. The following instructional modes should help teachers emphasize process over product and focus on the learner.

- Communicate about the learning process. Ask students what it means to them to learn something. How do they learn best? Have them discuss what kinds of experiences help them to learn efficiently.
- Reflect. Students need to think about their own learning processes. They need to be able to self-evaluate and self-regulate. Teachers often presume that if a student gives

up on a task it is a matter of self-discipline. There are times when quitting is the most intelligent thing to do. If you don't know where you are going and have no sense of whether you are getting there, it is best to stop and rethink your approach.

Classroom Practices. Here are some active roles that students can serve in the classroom.

- Encourage students to assist in establishing reliable communication. Students can appreciate the need for precision in communication, and they can look out for ambiguities. They can seek clarification.
- Help students become defensive learners. Preconceptions are often easier to dislodge when students are engaged. If students learn how to explore the internal consistency of their own models, then they can root out many errors on their own.
- Have students consciously participate in the acquisition and structuring of knowledge. Warn students of common misconceptions. Discuss problem solving. Encourage students to look for patterns and relationships between ideas. Have students seek categories and think about thinking. Discuss what is meant by "structuring".
- Help students develop self assessment skills. Have students grade themselves. Ask them to evaluate their own study habits or group dynamics. Just as you would encourage students to check their answer to a problem, they should be encouraged to reflect on any task and evaluate their performance.

IX. Meta-communicating with Students

Research Results. We have shown that first year university physics students can learn to write qualitative concept-based strategies before they solve problems. Although these students have completed high school, their overall skills are not significantly more advanced than those of most high-school students. Students can be sensitized to the importance of principles for solving problems, and to the value of concepts for judging the appropriateness and applicability of equations [Leo96b].

Pedagogy. Meta-communication is communicating about communicating, thinking about thinking, talking about problem solving, discussing effective interaction modes, etc. Meta-communication is the mode many teachers use to address motivational issues, but usually this is done infrequently and with individuals only. We recommend broadening its scope and its use in the classroom. Meta-communication is a mode we can use to keep students engaged and help students structure their knowledge.

Instructional Modes. The following modes can help teachers meta-communicate with students.

- Communicate about the learning process. In other words, meta-communicate. Discuss with students how they might help each other learn. Discuss the kinds of

questions or tasks they find interesting and rewarding. Are they able to correctly predict that they can solve a problem or accomplish a task before they attempt it? What makes it possible for them to do this?

- Plan, Justify, and Strategize. When students plan how they will solve a problem, justify their plan, or develop a strategy for solving a problem, they are thinking about problem solving. Suggest to them the global strategy of shifting their focus from trying to solve a problem to considering what is making this problem difficult for them. Often this induces a sufficiently different perspective that the problem is now amenable to solution.

- Reflect. Any form of reflection on the learning process is meta-communication. Perhaps the most important question for students to consider is what motivates them. Do they feel elated when correct and dismayed when incorrect? Why?

Classroom Practices. Here are some of the important topics to communicate.

- Communicate with students about developing and interrelating different representations. Using multiple representations helps interrelate knowledge and strengthens connections with personal experience and real-world situations. Science, especially secondary-school science, tends to focus too much attention on equations and not enough attention on the linguistic representation. Students should therefore know why they should explain predictions and describe observations as much as possible. Students tend not to use diagrams and sketches to analyze situations or solve problems, so teachers should discuss the value of drawings, diagrams, and graphs to reason about physical situations. Students should understand why efficient and effective problem solving involves choosing an optimal representation.

- Encourage students to establish a personal learning style. Students have spent years in the school system before entering your classroom. They have developed various coping strategies for surviving instruction. Unfortunately, most of these strategies are not useful for developing deep understanding or concept-based problem solving. New strategies are needed, and students can help determine what modes work best for them. Students should be more experimental, and they should try to identify the types of experiences that are most effective.

- Talk to students about participating in the learning process. Students tend to be somewhat addicted to a means–ends approach, which often inhibits thoughtful engagement in the learning process. Many students don't appreciate the value of wrong answers, and often don't realize that correct answers can be unreliable, because it's usually easy to get the right answer by guessing or by using incorrect reasoning. Therefore, discuss the reasons that engagement is important and reward students for thinking.

- Make implicit knowledge explicit. Good students seek and notice patterns. The rest need the patterns pointed out explicitly. More importantly, they need to appreciate the value of seeking patterns, so that they can engage in looking for patterns themselves.

Make assumptions explicit, and discuss why it is important for students to be aware of the assumptions they make while analyzing situations.

Conclusion

If you are an experienced teacher, you probably did not learn all that much that is new by reading this supplement. In many ways teachers are very much like students. Both have a tremendous amount of knowledge stored in the form of experiences. Also, both frequently fail to classify and categorize those experiences to perceive patterns that can be generalized into principles. If the above has caused you to reflect upon your own experiences and wonder how students might interpret your comments and behaviors as a teacher, then we have accomplished our major objective. We have tried to present the case for our view of instruction as a cooperative dialog between teacher and student, an exchange-interaction that benefits both. Finally, we hope you find some of the suggested classroom practices helpful. We would certainly appreciate receiving your comments regarding any that you try.

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